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*Smart Wheelchair Exoskeleton for ALS Patients*

Gull, Muhammad Ahsan; Bai, Shaoping; Mrachacz-Kersting, Natalie; Blicher, Jakob

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# WEXO: Smart Wheelchair Exoskeleton for ALS Patients

MA.Gull
Dept. of Materials and Production
Aalborg University
Denmark
mag@m-tech.aau.dk

Shaoping Bai
Dept. of Materials and Production
Aalborg University
Denmark
shb@m-tech.aau.dk

N. Mrachacz-Kersting
Dept. of Health Sciences and Technology
Aalborg University
Denmark
nm@hst.aau.dk

Jakob Blicher
Center of Functionally Integrative Neurosciences
Aarhus University
Denmark
jbli@cfin.au.dk

## ABSTRACT
This paper introduces a novel wheelchair mounted exoskeleton (WEXO) to aid patients with mobility impairment and limitation of their upper extremity. The WEXO integrates a four-degree-of-freedom (DOF) exoskeleton arm and a soft exoskeleton glove to assist arm motion and hand grasping. The kinematics of the WEXO were quantified using the Denavit-Hattenberg (DH) parameters and the possible input control modalities were investigated for accurate intention detection of ALS patients.

## Keywords
Upper Body Exoskeleton, Wheelchair Mounted Exoskeleton, BCI, EEG.

## 1. INTRODUCTION
Locomotion and manipulation are challenging tasks for patients suffering from chronic neuromuscular disease and physical disabilities. Neuro-motor dysfunction like Amyotrophic Lateral Sclerosis (ALS), cerebral palsy and muscular dystrophy have a significant impact on the patient's quality of life. Additionally, medical care and services require considerable financial resources that have a direct impact on our community. Thus, robotic assistive technology represents a promising solution for people with motor dysfunction to facilitate their activities of daily living (ADL) and their participation in the community. Assistive devices for the rehabilitation of motor dysfunction have been developed with growing interests and applications [1], especially in the form of smart wheelchair mounted robots. Robotic wheelchairs can assist the user's motion to allow them to interact effectively with their external environment, particularly, for reaching and grasping tasks.

A number of wheelchairs mounted robots have been developed by means of robotic manipulators (WMRM). For example, a 9-DOF WMRM II [2], was developed by the University of South Florida, to support elderly patients in autonomous navigation and manipulation while performing ADL using visual servoing. The robot incorporates with adjustable link length to make it have a large adaptability to users of different sizes. Another example is Raptor [3], a 4-DOF commercially available manipulator for wheelchair application. This supports spinal cord injured patients during a wide range of ADLs, such as grasping and pouring water, using Sip and Puff technology. Due to the unavailability of encoders, Raptor cannot be controlled precisely within Cartesian coordinates. KARE II [4], a 6-DOF manipulator driven by visual servoing or electromyography (EMG) signals is able to support four basic tasks autonomously; drinking, grasping a pen from the floor, as well as turning on and off a light switch. The Manus ARM [1] is another commercially available WMRM which is designed to assist patients suffering from limited motor dexterity in performing their ADL. This [5] is a six-degrees-of-freedom (DOF) wheelchair mounted robotic arm system with a weight of 14.3 kg for a maximum payload of 1.5 kg. The maximum reach of the end-effector is 800 mm, which can be controlled with two different types of user interfaces; namely a local control interface and a remote operator controller. The FRIEND IV [6] is a seven-DOF wheelchair mounted robotic arm which is designed to assist quadriplegic people for physical tasks. The end-effector is an adapted version of an industrial parallel gripper which facilitates handling of books, such as transferring books from a cart to a shelf and vice versa. The JACO arm [7] is a seven-DOF robotic arm system developed by KINOVA and consists of six lightweight interconnected carbon fiber links coupled to a three-fingered end-effector. The maximum opening of the fingers is 12 cm and each finger can move independently. The JACO arm is usually controlled by a three-axes joystick which can be complex to use, especially for people with mild cognitive impairments.

**Figure 1. WEXO prototype for ALS patients**

All aforementioned WMRMs aim to assist ALS patients in the locked-in state with robotic manipulator to support ADL. Upper body exoskeletons on the other hand, are wearable robotics that replicate the skeletal structure of the user's upper limb. Unlike

WMRMs, this type of device is coupled with the user's upper limb to assist the movement at joint level.

This paper presents a novel wheel chair mounted exoskeleton (WEXO) design, which is an anthropomorphic kinematic structure and compatible with the human upper body torso. The ergonomic design of WEXO enables the user to perform large range of motion movements and provides assistance in ADL for reaching and grasping movements (Figure 1). In the WEXO, a novel shoulder mechanism is introduced to overcome the recurrent singularity issues of a spherical joint. The kinematics of the WEXO are derived with the DH parameters. Finally, a possible control strategy of WEXO is presented.

## 2. DESIGN OF WHEELCHAIR MOUNTED UPPER BODY EXOSKELETON

A new wheelchair mounted exoskeleton, WEXO has been developed at Aalborg University, Denmark. The WEXO consists of two sub-systems; one four-DOF exoskeleton arm and one three-finger soft exoskeleton glove. The system has four active and one passive DOFs. The four active DOFs are used to assist shoulder extension/flexion and abduction/adduction, and elbow extension/flexion by coupling the upper limb to a rigid exoskeleton mechanism. Grasping is supported by a soft robotic glove developed by *Bioservo Technologies* [8]. Shoulder internal and external rotations are passively performed with a double parallelogram linkage [9]. The range of motion (ROM) for each mechanical joint (Table 2) attains 99% of the range of motion required for ADL.

Maxon EC-60 and EC-45 flat brushless DC motors were selected along with two different types of harmonic transmission drivers (Table 2), to meet the speed and torque requirements for ADL. Two custom design soft orthosis cuffs ensure a comfortable physical connection between the user and WEXO at the upper arm and forearm level.

## 3. KINEMATIC MODELING AND ANALYSIS

The kinematic diagram of WEXO is shown in Figure 2. The kinematics of WEXO were analyzed with the Denavit-Hartenberg (DH) parameters given in Table 1, where $L_u$ and $L_f$ are the upper arm and forearm lengths respectively. The transformation matrix of the mechanism can be readily achieved which gives complete information about position and orientation of WEXO. Thus, the set of equations gives all reachable points by the exoskeleton for the given joint angles:

**Table 1. DH Parameters of WEXO**

| *Link i* | $a_i$ | $\alpha_i$ | $d_i$ | $\theta_i$ |
|---|---|---|---|---|
| *1* | *0* | *-π/2* | *0* | $\theta_1$ |
| *2* | *0* | *π/2* | *0* | $\theta_2$ |
| *3* | $L_u$ | *0* | *0* | $\theta_3$ |
| *4* | $L_f$ | *0* | *0* | $\theta_4$ |

$$\begin{cases} p_x^0 = L_u C_1 C_2 C_3 - L_u S_1 S_3 - L_f C_4 (S_1 S_3 - C_1 C_2 C_3) \\ \qquad - L_f S_4 (C_3 S_1 + C_1 C_2 S_3) \\ p_y^0 = L_f S_4 (C_1 C_3 - C_2 S_1 S_3) + L_u C_1 S_3 \\ \qquad + L_f C_4 (C_1 S_3 + C_2 C_3 S_1) + L_u C_2 C_3 S_1 \\ p_z^0 = -S_2 \left( L_f C_{(3+4)} + L_u C_3 \right) \end{cases} \tag{1}$$

where

$C_i = cos\theta_i$ $and$ $S_i = sin\theta_i$

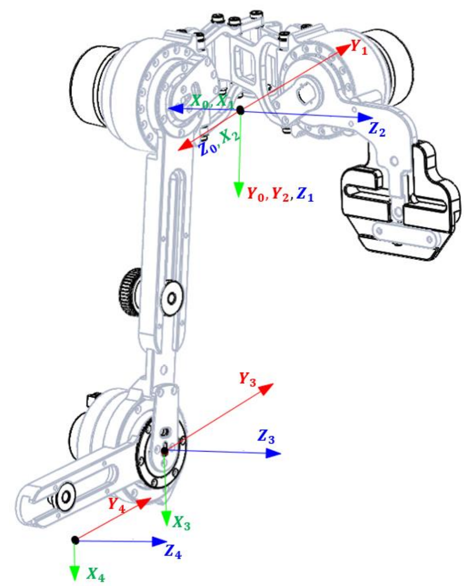


**Figure 2. Kinematic diagram of WEXO**

The velocity of angular velocity of the forearm of the exoskeleton is

$$\boldsymbol{\omega} = \mathbf{J}.\dot{\boldsymbol{\theta}} \tag{2}$$

where, $\dot{\boldsymbol{\theta}} = [\dot{\theta}_1 \;\; \dot{\theta}_2 \;\; \dot{\theta}_3 \;\; \dot{\theta}_4]^T$ represents the joint angular velocity, $\mathbf{J}$ is the Jacobian matrix and $\boldsymbol{\omega} = [\omega_1 \;\; \omega_2 \;\; \omega_3]^T$ is the output angular velocity of WEXO. The Jacobian matrix is given by.

$$\mathbf{J} = \begin{bmatrix} J_{11} & J_{12} & J_{13} & J_{14} \\ J_{21} & J_{22} & J_{23} & J_{24} \\ J_{31} & J_{32} & J_{33} & J_{34} \end{bmatrix} \tag{3}$$

The elements of Jacobian matrix are:

$$J_{11} = -L_f S_4 (C_1 C_3 - C_2 S_1 S_3) - L_u C_1 S_3 - L_f C_4 (C_1 S_3 + C_2 C_3 S_1) - L_u C_2 C_3 S_1$$

$$J_{12} = -C_1 S_2 (L_f C_{(3+4)} + L_u C_3$$

$$J_{13} = L_f S_4 (S_1 S_3 - C_1 C_2 C_3) - L_u C_3 S_1 - L_f C_4 (C_3 S_1 + C_1 C_2 S_3) - L_u C_1 C_2 S_3$$

$$J_{14} = L_f S_4 (S_1 S_3 - C_1 C_2 C_3) - L_f C_4 (C_3 S_1 + C_1 C_2 S_3)$$

$$J_{21} = L_u C_1 C_2 C_3 - L_u S_1 S_3 - L_f C_4 (S_1 S_3 - C_1 C_2 C_3) - L_f S_4 (C_3 S_1 + C_1 C_2 S_3)$$

$$J_{22} = -S_1 S_2 (L_f C_{(3+4)} + L_u C_3)$$

$$J_{23} = L_u C_1 C_3 - L_f S_4 (C_1 S_3 + C_2 C_3 S_1) + L_f C_4 (C_1 C_3 - C_2 S_1 S_3) - L_u C_2 S_1 S_3$$

$$J_{24} = L_f C_1 C_3 C_4 - L_f C_1 S_3 S_4 - L_f C_2 C_3 S_1 S_4 - L_f C_2 C_4 S_1 S_3$$

**Table 2. WEXO range of motion, transmissions specification and functional requirements**

| ***Supported movements*** | ***Min ROM (Deg)*** | ***Max ROM (Deg)*** | ***Actuator*** | ***Gear type*** | ***Speed (rpm)*** | ***Rated Torque/force*** |
|---|---|---|---|---|---|---|
| Shoulder (Int-Ext Rot) | $-30^o$ | $60^o$ | - | - | User defined | User defined |
| Shoulder (Fle-Ext) | $-60^o$ | $170^o$ | EC-60 | LCS-17-18 | 69.8 | 11.2 *Nm* |
| Shoulder (abd/add) | $-10^o$ | $170^o$ | EC-60 | CSD-25-50 | 43.6 | 18.0 *Nm* |
| Elbow (Fle-Ext) | $0^o$ | $135^o$ | EC-45 | CSD-25-50 | 42.7 | 10.0 *Nm* |
| Grasping | Follow Actual Hand ROM | | Servos | - | - | 20 *N* |

$$J_{31} = 0$$

$$J_{32} = -C_2(L_f C_{(3+4)} + L_u C_3)$$

$$J_{33} = S_2(L_f S_{(3+4)} + L_u S_3)$$

$$J_{34} = L_f S_{(3+4)} S_2$$

The developed model is used in the motion control of the exoskeleton arm.

## 4. Actuation and Control

In order to achieve the specified torque and speed requirements of WEXO, several combinations of actuators and harmonic drives were investigated. After careful analysis of end-user requirements for ADL and simulation of upper limb movement, assistance with 5 kg payload were used to identify the desired speed and torque. Thus, to make an overall implementation of ergonomic WEXO feasible, all active joints are powered by harmonic gears (CSD-25-50-2) and brushless dc-motors (Table 2). To enable the actuators to run the system safely and smoothly back drivability of the harmonic gear (CSD-25-50-2) was implemented to prevent the user from being locked even though the motors are powered off [10]. Further a reliable control of the physical interaction between the exoskeleton and its environment is crucial for the successful assistance of ADL.

A control strategy was proposed for the WEXO. This is a BCI based control, as shown in Figure 3. The control system is under development. Further clinical testing on the physical assistance of ALS patients is planned to be conducted upon the system development.

## 5. DISCUSSION

Progresses with exoskeletons allow the assistance of neuromuscular impairments. However, the natural mobility and the achievable range of motion, especially about the shoulder joint, remains the principal challenge of upper limb exoskeleton. The presented WEXO introduces a potential solution to assist the shoulder girdle movement [9]. The range of motion of the shoulder joint is 90° for abduction/adduction and 110° for internal/external rotation, which allows adequate mobility of the user's upper limb. The elbow joint consists of a single revolute joint aligned with the user's elbow joint and, with a comparable range of motion. The unique combination of the exoskeleton mechanism and a soft robotic glove provides a kinematically complementary solution for physical human robot interaction (pHRI) by overcoming the inter-subject variability of joint center of rotation and individual's torso dimensions. Compatible pHRI and an adaptable design of the mechanism enables the user to manipulate effectively while maneuvering of mobile platforms.

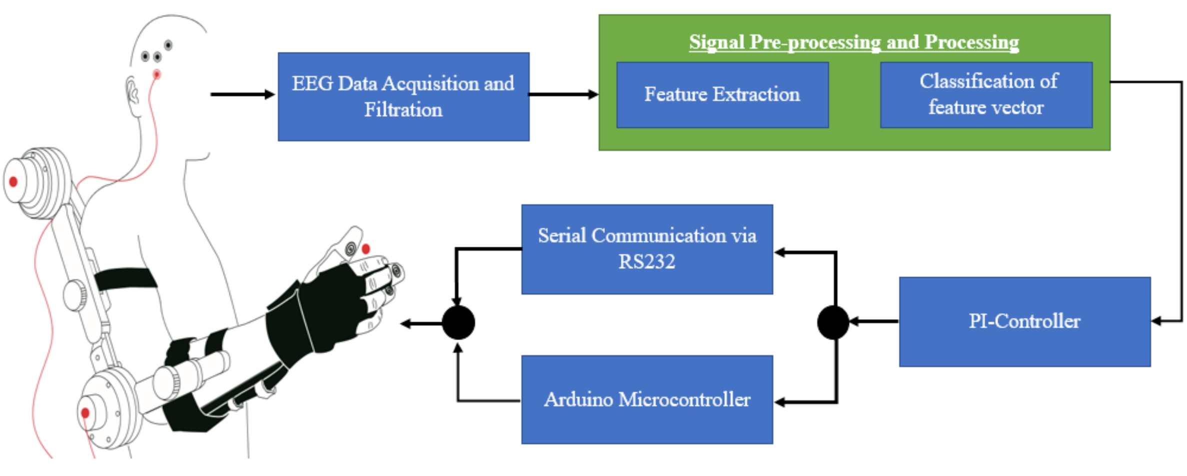


**Figure 3. Schematic diagram for proposed wheelchair mounted exoskeleton (WEXO) control.**

The stability and high performance control of the wheel chair mounted exoskeleton is an essential requirement to achieve as it operates in a close physical interaction with the user. Different control input modalities have been investigated, including force sensitive resistors (FSRs), tactile sensors, electromyography (sEMG) and electroencephalography (EEG) for optimal user intention detection. Control input from force sensitive resistors and sEMG sensors directly represents the applied force and muscle activity of the patient respectively. Numerous applications such as wheelchair, prosthesis and exoskeletons show the effectiveness of such control techniques. However, FSR and EMG based control techniques have some disadvantages depending upon the physical state of the user and application. Patients suffering ALS and neuromuscular dystrophy are unable to generate muscle signal of sufficient strength, thus may not be able to use WEXO. Additionally, people with the residual muscular activities do not completely relay on the FSR and EMG based control techniques because undesired tremor and muscular fatigue can affect the amplitude and the frequency spectrum of control input [11]. It is expected that EEG based control input method, shown in Figure 3, can compensate the missing volunteer muscular movement and still can be used to reject the artifacts including muscular fatigue and unwanted tremor

## 6. CONCLUSION

A wearable wheelchair mounted exoskeleton has been proposed which can assist the user in ADL without affecting freedom and mobility of torso. A novel shoulder mechanism has been used to accommodate shoulder movement and provide wide range of motion. Moreover, an EEG based control strategy is under development to allow for control of WEXO for the patient suffering from the severe neuromuscular disease. Further system development and clinical testing on the physical assistance for ALS patients is planned to be conducted.

## 7. ACKNOWLEDGEMENT

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